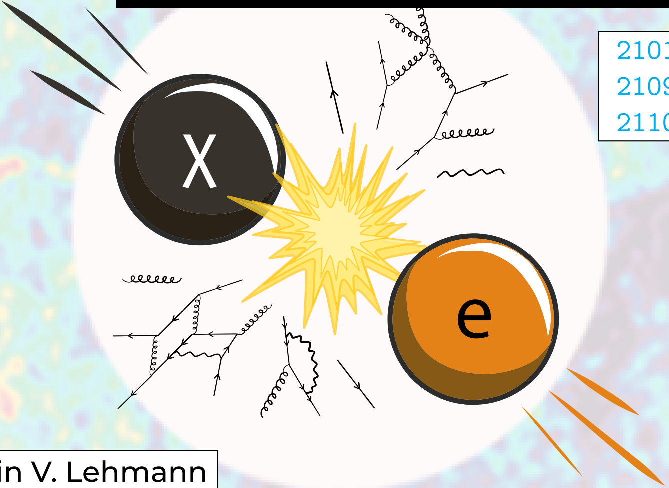
Direct detection of dark matter with superconducting nanowires

2101.08263
2109.04473
2110.01586

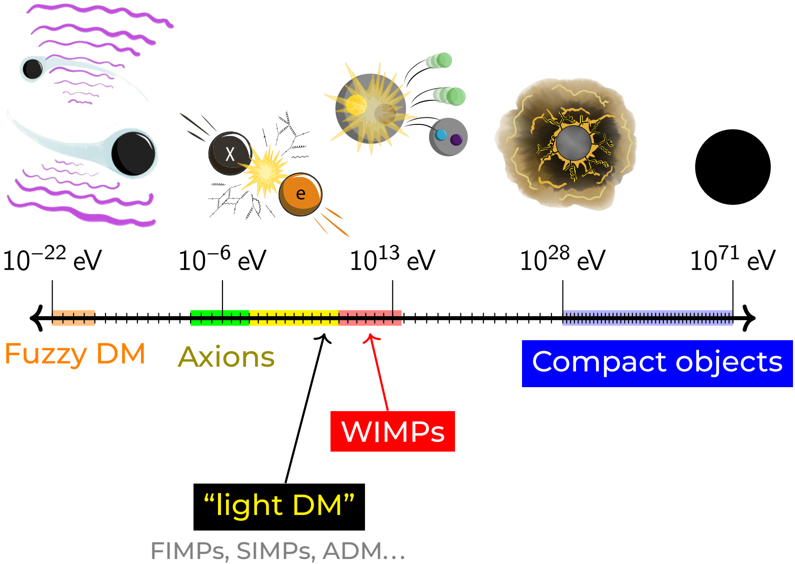


Benjamin V. Lehmann

UC SANTA CRUZ

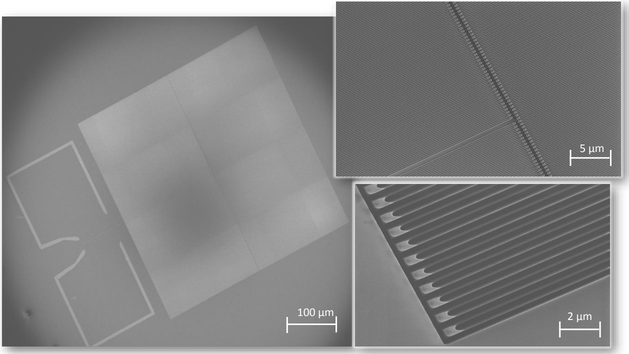
SCIPP
SANTA CRUZ INSTITUTE for PARTICLE PHYSICS
UC SANTA CRUZ

The dark matter parameter space

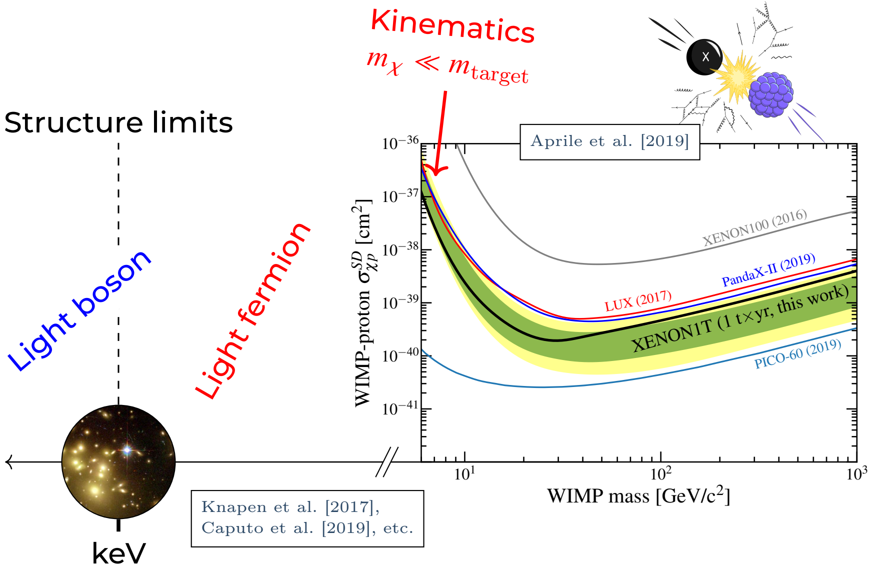


SNSPD detectors

Superconducting **N**anowire **S**ingle-**P**hoton **D**etector

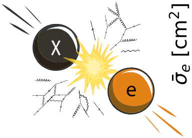


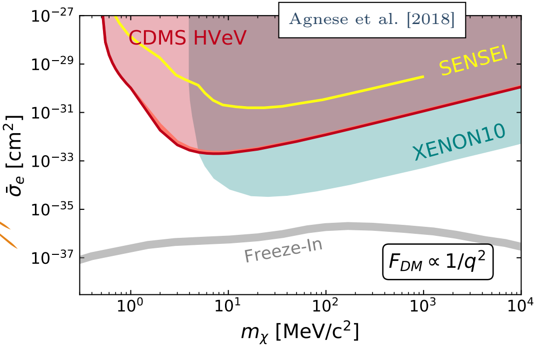
Sub-GeV DM


Kinematics
$m_\chi \ll m_{\text{target}}$
Structure limits
Light boson
Light fermion
keV
Knapen et al. [2017],
Caputo et al. [2019], etc.
Aprile et al. [2019]
X
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
WIMP-proton $\sigma^{SD}_{\chi p}$ [cm^2]
XENON100 (2016)
PandaX-II (2019)
LUX (2017)
XENON1T (1 t×yr, this work)
PICO-60 (2019)
10^1
10^2
10^3
WIMP mass [GeV/c^2]

Electron recoils for light DM

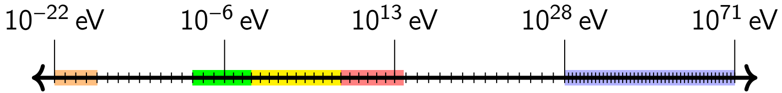
Match DM mass to target mass





MeV $\longrightarrow$ keV?

This talk in one slide



1. New approach to DM–electron scattering

Materials physics → keV-scale experiments

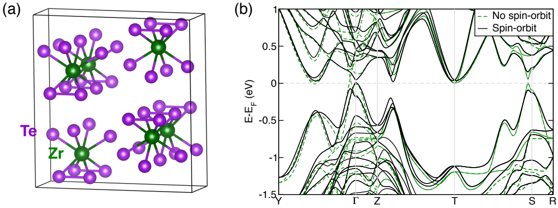
2. Superconducting detectors

Mechanism of operation and design considerations

3. Superconducting nanowires

New bounds and near-future prospects

All is not well with 1-particle language



Hochberg et al. [2018]

DM does not interact with just one particle.

- Complicated to compute *(collective modes!)*
- DM model dependence *(sometimes wrong!)*
- Each calculation is in a different language

$$|\chi\rangle|\Psi\rangle_{\text{detector}} \longrightarrow |\chi'\rangle|\Psi'\rangle_{\text{detector}}$$

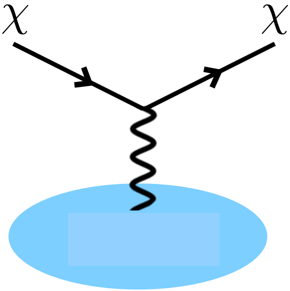
DM interactions in dielectrics

Yonit Hochberg, Yoni Kahn, Noah Kurinsky,
BVL, To Chin Yu & Karl Berggren

2101.08263, PRL

*See also Lin, Knapen & Kozaczuk, 2101.08275, PRD

Idea: separate *probe* and *response*



Response described by **complex dielectric function,**

$$\epsilon(\mathbf{q}, \omega) = \frac{V_{\text{applied}}}{V_{\text{applied}} + V_{\text{induced}}}$$

$\mathbf{q}$ = momentum transfer
ω = deposited energy

Same quantity as in ordinary screening

 Hochberg+ & **BVL** 2101.08263; Lin, Knapen & Kozaczuk 2101.08275

DM scattering rate

$$\Gamma = \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3} |V(q)|^2 \left[2\frac{q^2}{e^2} \underbrace{\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q},\omega_\mathbf{q})}\right)}_{\text{“Loss function” } \mathcal{W}} \right]$$

❶ Predictable: ϵ admits analytical approximations

Random phase approximation / Lindhard model, Drude model…

❷ Empirical: ϵ is directly measurable

EELS, X-ray scattering…

❸ Flexible: works for many targets, most DM models

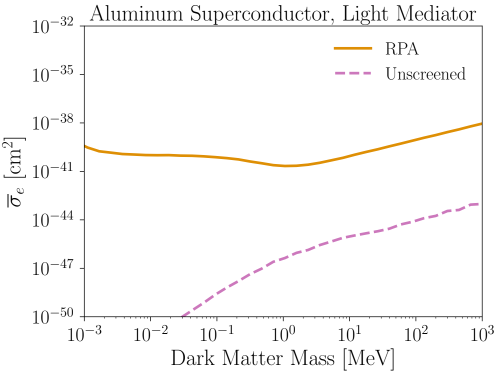
$$V(q) \simeq \frac{g_\chi g_e}{q^2 + m_{\mathrm{med}}^2}$$ *(spin-independent)*

❹ Inclusive: ϵ contains **all** collective modes

Hochberg+ & **BVL** 2101.08263; Lin, Knapen & Kozaczuk 2101.08275

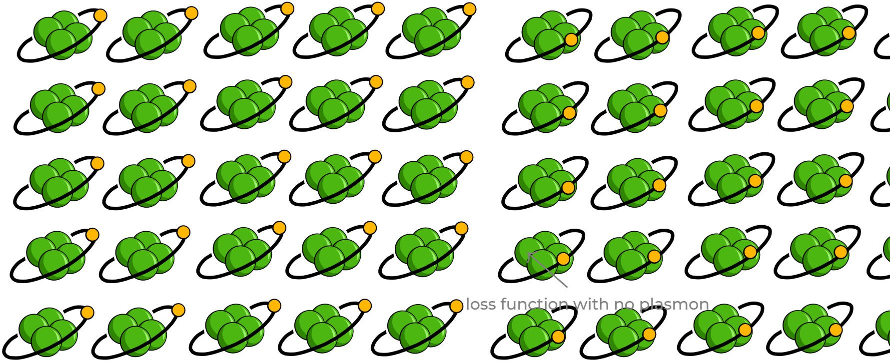
Understanding ϵ — screening

Just like E&M!



 Hochberg+ & **BVL** 2101.08263

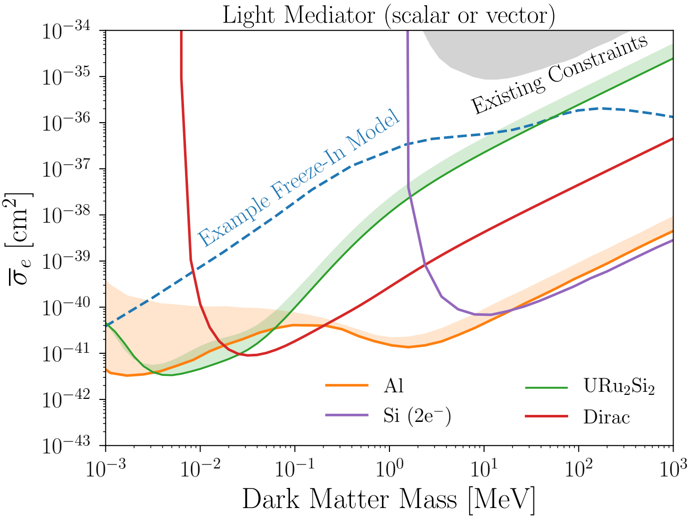
Understanding ϵ — plasmons



A **collective oscillation** of electrons

Shows up as a resonance in the **loss function**

Projected reach for ideal experiments



 Hochberg+ & **BVL** 2101.08263

Nearly ideal:

Superconducting detectors

Yonit Hochberg, Eric David Kramer, Noah Kurinsky & **BVL**

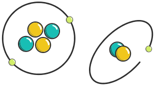
2109.04473

Yonit Hochberg, **BVL**, Ilya Charaev, Jeff Chiles,
Marco Colangelo, Sae Woo Nam & Karl Berggren

2110.01586

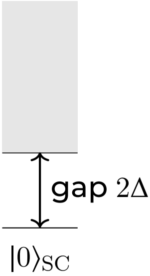
Superconductors: simple version

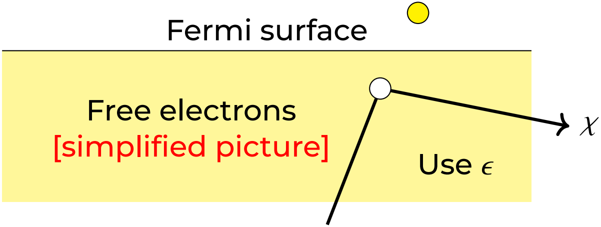
Central idea of direct detection:
DM induces measurable transitions



e.g. ionization for atomic targets

“Cooper-pair breaking”
Low threshold from gap $2\Delta \sim \text{meV}$

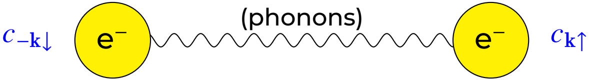




 Hochberg+ & **BVL** 2109.04473

Nature of the excitations

"Broken Cooper pairs"



Below T_C, transition to superconducting vacuum $|0_{\rm BCS}\rangle$, with a condensate of Cooper pairs: $\langle c_{-\mathbf{k}\downarrow} c_{\mathbf{k}\uparrow}\rangle \neq 0$.

$$\mathcal{H} = \sum_{\mathbf{k}\sigma} \xi_{\mathbf{k}} c^*_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{k}\boldsymbol{\ell}} V_{\mathbf{k}\boldsymbol{\ell}} \left(c^*_{\mathbf{k}\uparrow} c^*_{-\mathbf{k}\downarrow} b_{\boldsymbol{\ell}} + b^*_{\mathbf{k}} c_{-\boldsymbol{\ell}\downarrow} c_{\boldsymbol{\ell}\uparrow} - b^*_{\mathbf{k}} b_{\boldsymbol{\ell}} \right)$$

Diagonalize $\mathcal{H}$ with $\begin{cases} c_{\mathbf{k}\uparrow} = u^*_{\mathbf{k}} \gamma_{\mathbf{k}0} + v_{\mathbf{k}} \gamma_{\mathbf{k}1} \\ c^*_{-\mathbf{k}\downarrow} = -v^*_{\mathbf{k}} \gamma_{\mathbf{k}0} + u_{\mathbf{k}} \gamma^*_{\mathbf{k}1} \end{cases}$ *Bogoliubov quasiparticles*

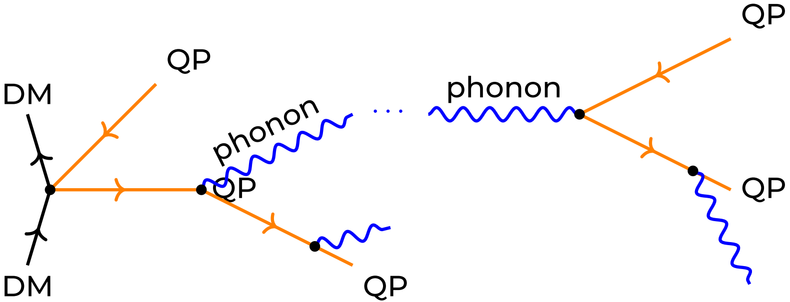
$$|\chi\rangle|0_{\rm BCS}\rangle \longrightarrow |\chi\rangle|{\rm QP}_1,\, {\rm QP}_2\rangle$$

 Hochberg+ & **BVL** 2109.04473

Down-conversion

What does the final state look like?

1. DM interaction produces pair of QPs
2. Energetic QPs relax by emission of phonons
3. Energetic phonons relax by QP pair production



Final state consists of numerous QPs and phonons

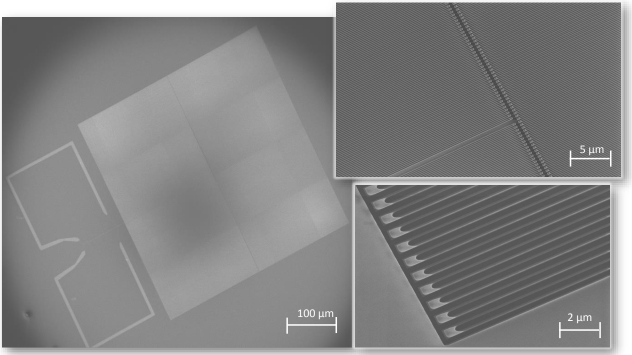
Superconducting nanowires

Yonit Hochberg, **BVL**, Ilya Charaev, Jeff Chiles,
Marco Colangelo, Sae Woo Nam & Karl Berggren

2110.01586

SNSPD detectors

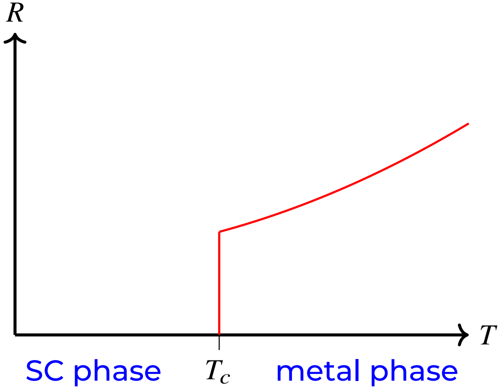
Superconducting **N**anowire **S**ingle-**P**hoton **D**etector



Real new constraints with < 8-day run, $4.3\,\mathrm{ng}$

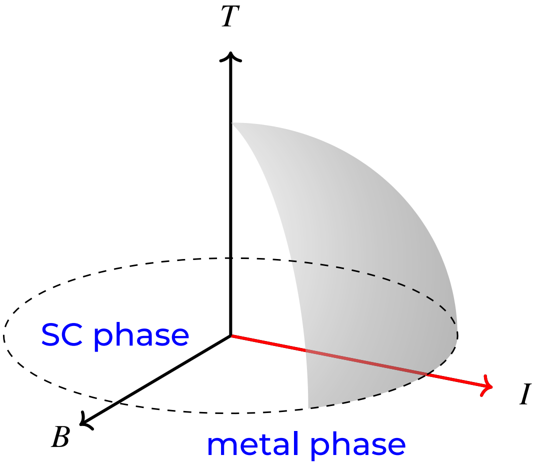
4 dark counts observed (interpreted as background)

 Hochberg+ & **BVL** 2110.01586



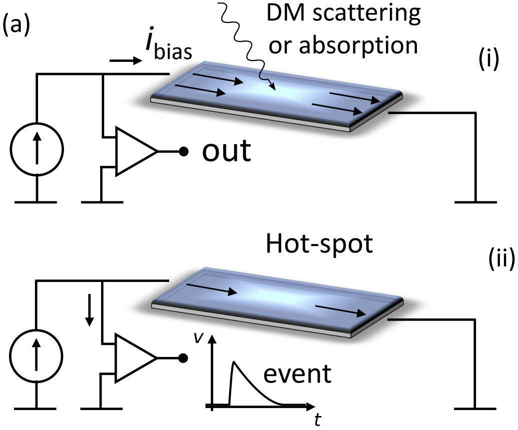
 Hochberg+ & **BVL** 2110.01586

SNSPD operation



Superconducting wire current-biased near transition

SNSPD operation

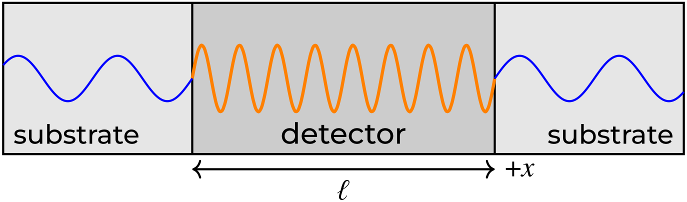


Extremely low dark count rate

 Hochberg+ & **BVL** 2110.01586

DM scattering in a thin layer

Detector response depends on **geometry**



Back to the macroscopic picture:

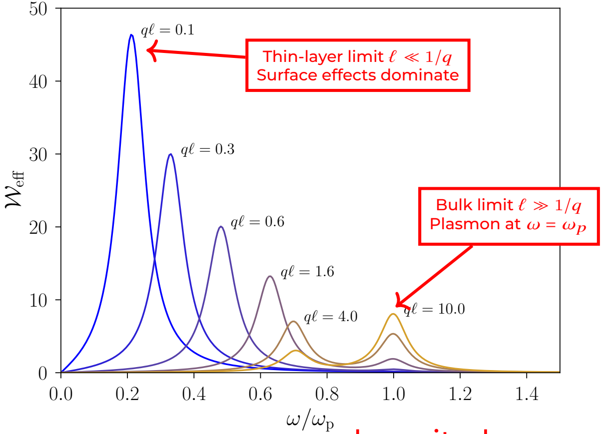
1. Poisson equation $\epsilon\, \nabla^2 \phi = \phi_0 e^{i(\mathbf{q}\cdot\mathbf{x}-\omega t)}$
2. Use ansatz $\phi = \psi(x) e^{i(\mathbf{q}\cdot\mathbf{x}-\omega t)}$ and impose BCs
3. Compute time-averaged power dissipated

Effective loss function

$$\mathcal{W}_{\text{eff}} \equiv \frac{q^2}{\ell} \operatorname{Re}\left[-i\frac{1}{\rho}\int \mathrm{d}x \left(i\psi(x) + \frac{q_x}{q^2}\psi'(x)\right)\right]$$

Hochberg+ & **BVL** 2110.01586; Lasenby & Prabhu 2110.01587

Thin-layer response function



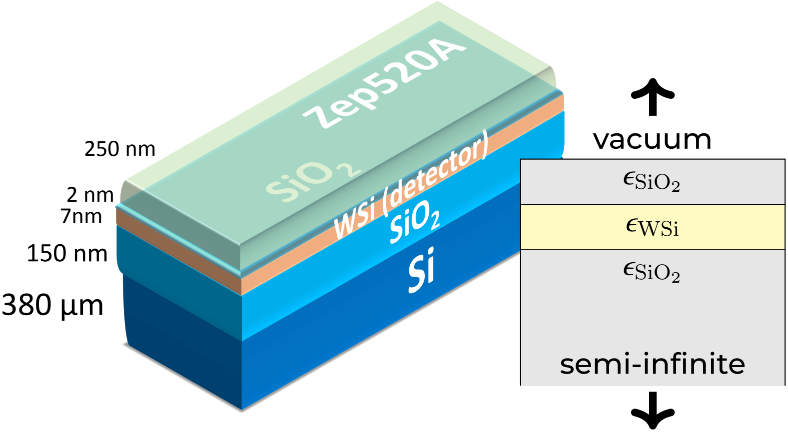
deposited energy

Hochberg+ & **BVL** 2110.01586; Lasenby & Prabhu 2110.01587

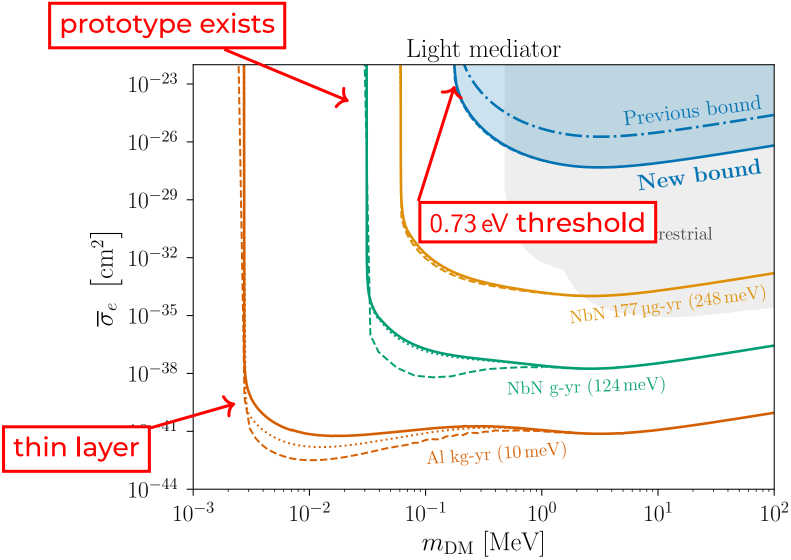
Geometric effects

Relevant for $q \lesssim 1/(7\,\mathrm{nm}) \approx 30\,\mathrm{eV}$

$\Longrightarrow$ biggest effect for $m_{\mathrm{DM}} \lesssim 100\,\mathrm{keV}$



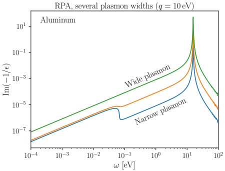
New constraints on DM scattering



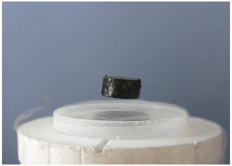
Hochberg+ & **BVL** 2110.01586

Conclusions

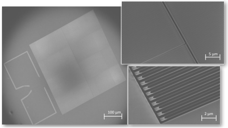
New experiments will powerfully probe light DM



Dielectric formalism
for light DM



Superconductors
as detectors



New constraints from
SNSPD devices

Nanowires can lead exploration of this regime

 Hochberg+ & **BVL** 2110.01586

References I

R. Agnese et al. First Dark Matter Constraints from a SuperCDMS Single-Charge Sensitive Detector. *Phys. Rev. Lett.*, 121(5):051301, 2018. doi: 10.1103/PhysRevLett.121.051301. [Erratum: Phys.Rev.Lett. 122, 069901 (2019)].

E. Aprile et al. Constraining the spin-dependent WIMP-nucleon cross sections with XENON1T. *Phys. Rev. Lett.*, 122(14):141301, 2019. doi: 10.1103/PhysRevLett.122.141301.

R. Caputo, T. Linden, J. Tomsick, C. Prescod-Weinstein, M. Meyer, C. Kierans, Z. Wadiasingh, J. P. Harding, and J. Kopp. Looking Under a Better Lamppost: MeV-scale Dark Matter Candidates. 3 2019.

Y. Hochberg, Y. Kahn, M. Lisanti, K. M. Zurek, A. G. Grushin, R. Ilan, S. M. Griffin, Z.-F. Liu, S. F. Weber, and J. B. Neaton. Detection of sub-MeV Dark Matter with Three-Dimensional Dirac Materials. *Phys. Rev. D*, 97(1): 015004, 2018. doi: 10.1103/PhysRevD.97.015004.

S. Knapen, T. Lin, and K. M. Zurek. Light Dark Matter: Models and Constraints. *Phys. Rev. D*, 96(11):115021, 2017. doi: 10.1103/PhysRevD.96.115021.

G. D. Mahan. *Many-particle physics*. Springer Science & Business Media, 2013.

Hidden sector

Dielectric details

1. Interaction Hamiltonian couples to electron density
2. Interaction is weak (very safe for DM)
3. Ion contribution to the material response is small

Under these conditions,

$$\Gamma = \sum_f \left| \langle f; \mathbf{p}'_\chi | \hat{H}_{\mathrm{int}} | 0; \mathbf{p}_\chi \rangle \right|^2 2\pi\delta(\omega_f + E'_\chi - E_\chi)$$

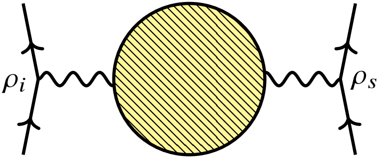
$$\hat{H}_{\mathrm{int}} = \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3} e^{i\mathbf{q}\cdot\mathbf{r}_\chi} V(\mathbf{q}) \hat{\rho}(\mathbf{q})$$

Dielectric function emerges

$$\sum_f \left| \langle f | \hat{\rho}(\mathbf{q}) | 0 \rangle \right|^2 \delta(\omega_f - \omega) = \frac{q^2}{\pi e^2} \,\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q}, \omega)} \right)$$

Hochberg+ & **BVL** 2110.01586

The dielectric function ϵ — macro



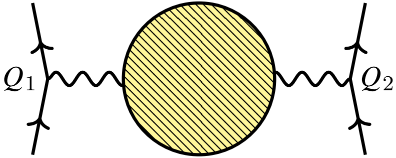
$$\begin{cases} i\mathbf{q}\cdot\mathbf{D}(\mathbf{q}) = 4\pi\rho_i(\mathbf{q}) \\ i\mathbf{q}\cdot\mathbf{E}(\mathbf{q}) = 4\pi[\rho_i(\mathbf{q}) + \rho_s(\mathbf{q})] \end{cases}$$

$$\epsilon(\mathbf{q}) \equiv \lim_{\rho_i\to 0} \frac{\mathbf{D}(\mathbf{q})\cdot\hat{\mathbf{q}}}{\mathbf{E}(\mathbf{q})\cdot\hat{\mathbf{q}}}$$

Linear regime: $$\epsilon(\mathbf{q}) \simeq \frac{\rho_i(\mathbf{q})}{\rho_i(\mathbf{q}) + \rho_s(\mathbf{q})}$$

 Hochberg+ & **BVL** 2110.01586

The dielectric function ϵ — micro



$$\Delta U \simeq Q_1 Q_2 \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{4\pi}{q^2} e^{i\mathbf{q}\cdot(\mathbf{R}_1 - \mathbf{R}_2)} \times$$
$$\left[1 - \frac{4\pi e^2/q^2}{\text{Vol}} \int_0^\beta d\tau \left\langle T_\tau \, \hat{\rho}_e(\mathbf{q},\tau) \, \hat{\rho}_e(-\mathbf{q},0) \right\rangle\right]$$

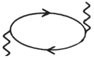
Compare with Coulomb interaction

$$V(\mathbf{R}_1 - \mathbf{R}_2) = Q_1 Q_2 \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{4\pi}{q^2} e^{i\mathbf{q}\cdot(\mathbf{R}_1 - \mathbf{R}_2)} \frac{1}{\epsilon(\mathbf{q})}$$

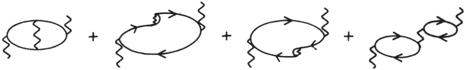
See e.g. Mahan [2013]

$$\frac{1}{\epsilon(\mathbf{q})} = 1 - \frac{4\pi e^2/q^2}{\mathrm{Vol}} \int_0^\beta \mathrm{d}\tau \left\langle T_\tau \, \hat{\rho}_e(\mathbf{q},\tau) \, \hat{\rho}_e(-\mathbf{q},0) \right\rangle$$

$P^{(1)}$ =



$P^{(2)}$ =



$$\epsilon(\mathbf{q}) = 1 - \frac{4\pi e^2}{q^2} P_{\mathrm{1PI}}(\mathbf{q})$$

Random phase approximation (RPA)

$$\epsilon_{\mathrm{RPA}}(\mathbf{q}) = 1 - \frac{4\pi e^2}{q^2} P^{(1)}(\mathbf{q})$$

The Lindhard function

$$\epsilon_{\rm RPA}(\mathbf{q},\omega) = 1 - \frac{1}{\Omega}\frac{e^2}{q^2}\sum_{\mathbf{k}}\sum_{\ell,\ell'}\frac{f^0(\mathcal{E}_{\mathbf{k+q},\ell'}) - f^0(\mathcal{E}_{\mathbf{k}\ell})}{\mathcal{E}_{\mathbf{k+q},\ell'} - \mathcal{E}_{\mathbf{k}\ell} - \omega - i\varepsilon}$$

Lindhard (RPA) dielectric function

$$\epsilon_{\rm RPA} \overset{T\to 0}{=} 1 + \frac{3\omega_{\rm p}}{q^2 v_{\rm F}}\left\{\frac{1}{2} + \frac{k_{\rm F}}{4q}\left[1 - \left(\frac{q}{2k_{\rm F}} - \frac{\omega + i\Gamma}{q v_{\rm F}}\right)^2\right]{\rm Log}\left(\frac{\frac{q}{2k_{\rm F}} - \frac{\omega+i\Gamma}{q v_{\rm F}} + 1}{\frac{q}{2k_{\rm F}} - \frac{\omega+i\Gamma}{q v_{\rm F}} - 1}\right)\right.$$
$$\left. + \frac{k_{\rm F}}{4q}\left[1 - \left(\frac{q}{2k_{\rm F}} + \frac{\omega + i\Gamma}{q v_{\rm F}}\right)^2\right]{\rm Log}\left(\frac{\frac{q}{2k_{\rm F}} + \frac{\omega+i\Gamma}{q v_{\rm F}} + 1}{\frac{q}{2k_{\rm F}} + \frac{\omega+i\Gamma}{q v_{\rm F}} - 1}\right)\right\}$$

Understanding ϵ — sum rules

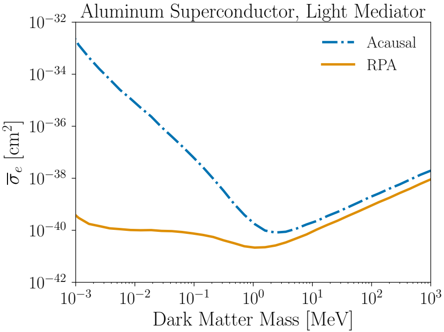
Causality $\longrightarrow$ analyticity $\longrightarrow$ Kramers–Kronig relations

ϵ satisfies sum rules

$$\int_0^\infty \mathrm{d}\omega\, \omega\, \mathrm{Im}\left(-\frac{1}{\epsilon}\right) = \frac{\pi}{2}\omega_\mathrm{p}^2$$

$$\lim_{\mathbf{q}\to 0} \int_0^\infty \mathrm{d}\omega\, \frac{1}{\omega}\, \mathrm{Im}\left(-\frac{1}{\epsilon}\right) = \frac{\pi}{2}$$

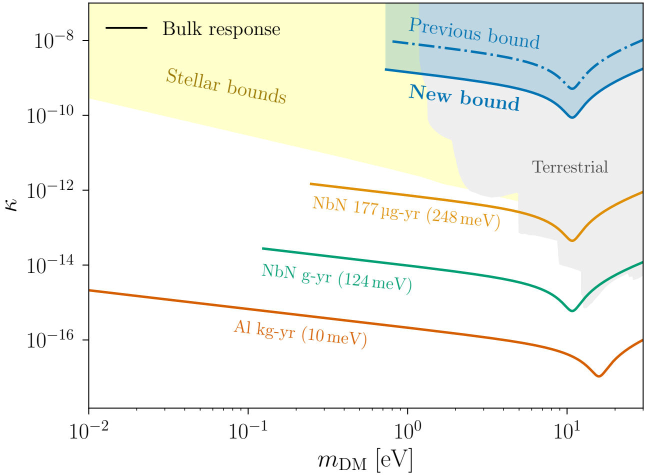
Quickly corrected literature projections



True reach is significantly better

Hochberg+ & **BVL** 2110.01586

New constraints: absorption



 Hochberg+ & **BVL** 2110.01586